## VOLTAGE TO CURRENT CONVERSION

Voltage controlled current sources (or VCCS's) can be useful for applications such as active loads for use in component testing or torque control for motors. Torque control is simplified since torque is a direct function of current in a motor. Current drive in servo loops reduces the phase lag due to motor inductance and simplifies stabilizing of the loop.

VCCS's using power op amps will assume one of two basic forms, depending on whether or not the load needs to be grounded.

## CURRENT SOURCE: FLOATING LOAD

Figure 1A illustrates the basic circuit of a VCCS for a floating load. The load is actually in the feedback path. $R_S$ is a current sense resistor that develops a voltage proportional to load current.
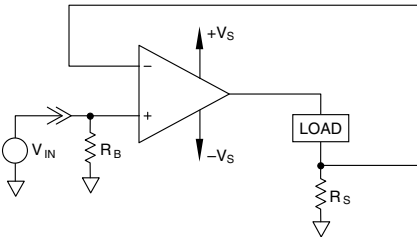


**FIGURE 1A.**  BASIC VCCS FOR FLOATING LOAD

Note the inclusion of resistor $R_B$ in Figure 1A and subsequent figures where non-inverting VCCS's are described. This resistor is present to prevent the non-inverting input from floating when the input voltage source is disconnected or goes to high impedance during the power on cycle. $R_B$ provides a path for input bias current of the amplifier and commands the amplifier output current to zero in cases where $V_{IN}$ is disconnected or goes to a high impedance. Figure 1B shows an implementation of a VCCS for a floating load. At low frequencies the added components Cf, Rd, and $R_F$ have no effect and are included only to insure stability. Considerations for these components are discussed in the section on "Stabilizing the Floating Load VCCS" covered later in this application note.
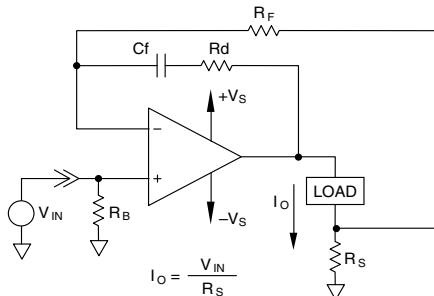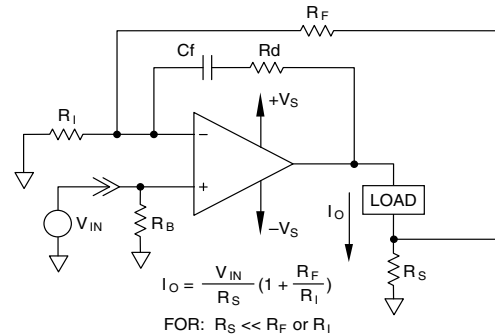


**FIGURE 1B.**  VCCS FOR FLOATING LOAD WITH STABILITY COMPENSATION

The amplifier's loop gain will force the voltage across $R_S$ to assume a value equal to the voltage applied to the non-inverting input, resulting in a transfer function of:

$$I_O = V_{IN}/R_S$$

Several variations are possible for this basic circuit. It is not necessary to have a direct feedback connection from $R_S$ to the inverting input; components can be included to raise the gain of the circuit. Figure 2 shows a higher gain version with its equivalent transfer function. Higher gain circuits will lose some accuracy and bandwidth, but can be easier to stabilize.
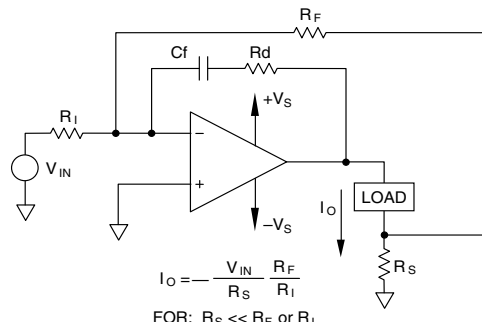


$$I_O = \frac{V_{IN}}{R_S}\left(1 + \frac{R_F}{R_I}\right)$$

FOR:  $R_S \ll R_F$ or $R_I$

**FIGURE 2.**  VCCS FOR FLOATING LOAD; INCREASED GAIN CONFIGURATION

Figure 3 shows an inverting VCCS. The input voltage results in an opposite polarity of current output. Just as in the case of inverting voltage amplifiers, the advantage of not having any common mode variation at the amplifier input is higher accuracy and lower distortion.
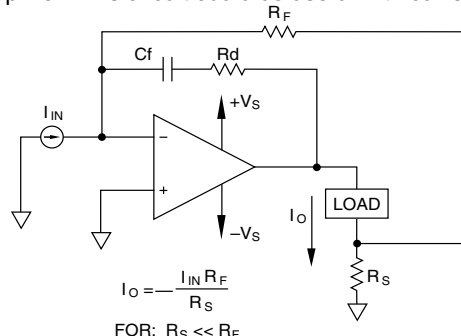


$$I_O = -\frac{V_{IN}}{R_S}\frac{R_F}{R_I}$$

FOR:  $R_S \ll R_F$ or $R_I$

**FIGURE 3.**  VCCS FOR FLOATING LOAD; INVERTING CONFIGURATION

Figure 4 is a current input version which is actually a CCCS, or current controlled current source. This is truly a current amplifier. This circuit could be useful with current output Digi-



$$I_O = -\frac{I_{IN} R_F}{R_S}$$

FOR:  $R_S \ll R_F$

**FIGURE 4.**  CCCS FOR FLOATING LOAD; INVERTING CONFIGURATION

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tal-to-Analog Converters (DAC's), or in any application where a current is available as an input.
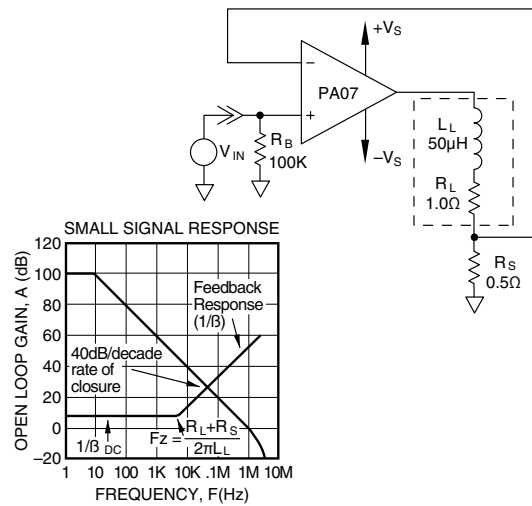
## STABILIZING THE FLOATING LOAD VCCS

Because the load is in the feedback loop on all of these circuits, it will have a significant effect on stability. If the load was always purely resistive, the analysis would be simple and many circuits would not require any additional components (such as Cf and Rd) to insure stability. In the real world however, we usually find ourselves using these circuits to drive such complex loads as magnetic coils and motors.

Stability analysis is most easily accomplished using **"Rate of Closure"** techniques where the response of the the feedback is plotted against the amplifier open loop gain. This technique uses information easily obtained on any amplifier data sheet.

Rate-of-closure refers to how the response of the feedback and amplifier Aol intersect. If the slope of the combined intersection is not over 20 dB per decade, the circuit will be stable.

For an example, consider the amplifier of Figure 1A. Assume a PA07 amplifier with a 0.5 ohm current sense resistor will be used to drive a 50 µH coil with 1 ohm of series resistance. In Figure 5 we have superimposed on the Aol graph of the PA07 the response of the load and sense resistor.



$$\beta_{DC} = \frac{.5}{1.5} = .333 \rightarrow 1/\beta = 9.5dB \quad Fz = \frac{1.0 + .5}{2 \ 50\mu H} = 4.77kHz$$

**FIGURE 5.** PLOTTING FEEDBACK RESPONSES

The intersection of the responses exhibits a combined slope of 40 dB per decade, leading to ringing or outright oscillation. Let's refer to that point as the "critical intersection frequency." Compensation for this circuit is best accomplished with an alternate feedback path; the response of which will dominate at the critical intersection frequency.

A good criteria for the response of the alternate feedback would be:
1. A response which dominates by at least an order of magnitude (20 dB) at the critical intersection frequency.
2. The alternate feedback response should have a corner occurring at a frequency an order of magnitude less than the critical intersection frequency.

To provide this response, the alternate feedback components have been selected to provide the compensating response illustrated in Figure 6. $A_B$ in Figure 6 is the dominant feedback path the amplifier will see in its closed loop configuration. $R_F$ merely acts as a ground leg return impedance for the alternate feedback loop, and should be a low value between 100 and 1000 ohms. Rd is then selected to provide the desired high

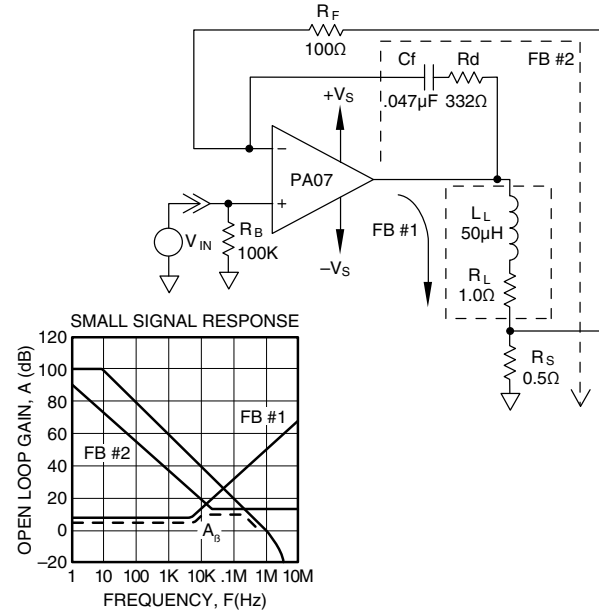frequency gain, and Cf is selected for the alternate feedback corner.



**FIGURE 6.** COMPENSATING THE AMPLIFIER

Note that these are similar to techniques used to stabilize magnetic deflection amplifiers described in Apex AN #5, **"Precision Magnetic Deflection."**

## CURRENT OUTPUT FOR GROUNDED LOAD

The VCCS for a grounded load is sometimes referred to as the **"Improved Howland Current Pump."** It is actually a differential amplifier which senses both input signal and feedback differentially.

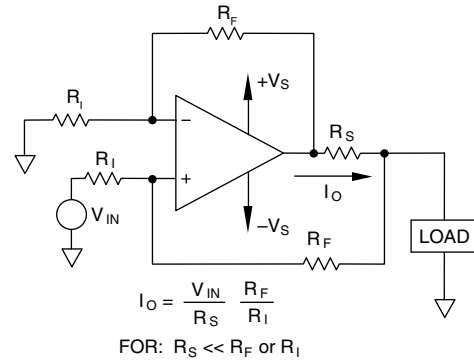Figure 7 shows a general example for this VCCS with its associated transfer function.



$$I_O = \frac{V_{IN}}{R_S} \ \frac{R_F}{R_I}$$

FOR: $R_S << R_F$ or $R_I$

**FIGURE 7.** VCCS FOR A GROUNDED LOAD

First among the special considerations for this circuit is that the two input resistors ($R_I$), and the two feedback resistors ($R_F$), must be closely matched. Even slight mismatching will cause large errors in the transfer function and degrade the output impedance causing the circuit to become less of a true current source.

As an example of the matching requirement, consider the actual example using PA07 in Figure 8. Matching the resistors as closely as tolerances permitted produced an output impedance of 43 K ohms. A 1% mismatch reduced output impedance to 200 ohms and introduced nearly 20% error into the transfer function.
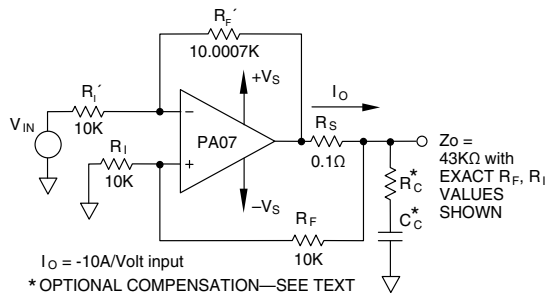
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**FIGURE 8.** ACTUAL PA07 VCCS

This suggests that matching to better than 0.1% is required which is probably best accomplished with prepackaged resistor networks with excellent ratio match. The circuit of Figure 8 actually required a slight amount of mismatch in the two ($R_F$) resistors to compensate for mismatches elsewhere, suggesting that the inclusion of a trimpot may be necessary to obtain maximum performance.

## STABILITY WITH THE GROUNDED LOAD CIRCUIT

The grounded load circuit is remarkably forgiving from a stability standpoint. Generally, no additional measures need to be taken to insure stability.

Any stability problems that do arise are likely to be a result of the output impedance of the circuit appearing capacitive. The equivalent capacitance can be expressed as follows:

$$Ceq = \frac{R_I + R_F}{2\pi foR_IR_S}$$

Where: fo = THE GAIN-BANDWIDTH PRODUCT OF THE AMPLIFIER

This capacitance can resonate with inductive loads, resulting most often in ringing problems with rapid transitions. The only effective compensation is a simple **"Q-snubber"** technique: determine the resonant frequency of the inductive load and output capacitance of the circuit. Then, select a resistor value one-tenth the reactance of the inductor at the resonant frequency. Add a series capacitor with a reactance at the resonant frequency equal to one-tenth of the resistor value. An alternate method would be to put a small inductor and damping resistor in series with $R_S$.

Also keep in mind that the equation favors larger values of $R_I$ and $R_S$, and the use of op amps with better gain-bandwidth to reduce effective capacitance. In circuits where good high frequency performance is required, this will necessitate increasing either or both $R_I$ and $R_S$ with the upper limits being established where stray capacitance and amplifier input capacitance become significant.

An infrequent second cause of instability in this circuit is due to negative resistance in the output impedance characteristic of the circuit. This problem can be solved by trimming the feedback resistors to improve matching.

## THE CURRENT MIRROR

The current mirror circuit is a handy device for generating a second current that is proportional to input current but opposite in direction.

The mirror in Figure 9 must be driven from a true current source in order to have flexible voltage compliance at the input. Any input current will attempt to develop a drop across R1 which will be matched by the drop across R2 causing the current through R2 to be ratioed to that in R1. For example, if R1 were 1.0 K ohm and R2 were 1 ohm, then 1 mA of input current will produce 1 Amp of output current.



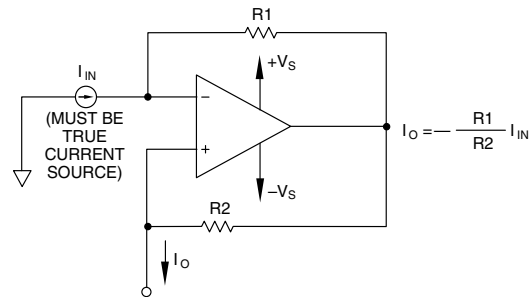**FIGURE 9.** CURRENT MIRROR

## RATE-OF-CLOSURE AND FEEDBACK RESPONSE

Rate-of-closure stability analysis techniques are a method of plotting feedback response against amplifier response to determine stability.

The closed loop gain of any feedback amplifier is given by:

$$Acl = Aol/(1-\text{ß}Aol)$$

Where: Aol IS THE OPEN-LOOP GAIN OF THE AMPLIFIER, AND Acl IS THE RESULTANT CLOSED LOOP GAIN

ß is a term describing the attenuation from the output signal to the signal fed back to the input (see Figure 10). In other words, ß is the ratio of voltage fed back to the amplifier over the amplifier's output voltage. (Vfeedback=ßVout)

In the examples used in this application note, the plotting of ß versus amplifier response is facilitated by plotting an equivalent closed loop response (1/ß) of the amplifier circuit and superimposing this response on the amplifier open loop response. This **"equivalent closed loop response"** is also referred to as noise gain, Av (n).

In the example in Figure 5, the curve referred to as feedback response is actually representative of the closed loop noise gain response of the amplifier due to the feedback network consisting of yoke and sense resistor. In Figure 6, an additional feedback response for Cf, Rd, and $R_F$ is plotted independently of all other responses. There are several important points to be noted in the use of these graphs:
1. In the case of multiple feedback networks such as in Figure 6, the response with the lowest noise gain at any given frequency will be the dominant feedback path. In Figure 6 this dominant feedback path is labelled $A_\text{ß}$.
2. Whenever the noise gain and open loop gain intersect with a combined slope, or rate of closure, exceeding 20 dB/decade, poor stability will result. 40 dB/decade will definitely oscillate since this represents 180 degrees of phase shift. An example of this is shown in Figure 5.
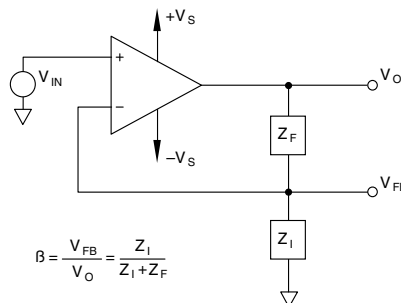


$$\text{ß} = \frac{V_{FB}}{V_O} = \frac{Z_I}{Z_I + Z_F}$$

**FIGURE 10.** FEEDBACK FACTOR, ß